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ANALYSIS AND REGIONALIZATION OF THE DIURNAL DISTRIBUTION OF TORNADOES IN THE UNITED STATES

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ABSTRACT

The central and eastern United States is divided into 157 overlapping square cells. Within each cell, the tornadoes that occurred from 1916 to 1964 are summed in 1-hr increments. The resulting histograms are subjected to harmonic analysis. The spatial distributions of the reduction of variance and phase angles of the harmonic components suggest substantial variation in the diurnal distribution of tornadoes. However, only two groups can be definitely isolated.

The Fourier representations of the histograms are classified numerically. From this analysis, three main diurnal distribution types and eight subtypes emerge. A preliminary attempt to account for these diurnal distributions is made; however, the degree of success is not notable and much work remains to be done.

1. INTRODUCTION

Since the surge of significant research on tornadoes began in 1949–50, a great deal of knowledge has accumulated in tornado climatology. The scope of the research is very wide, ranging from the synoptic climatology of composite pressure patterns to the probabilities of occurrence at a point in space and time. Nonetheless, the diurnal aspects of tornado occurrences have been essentially ignored.

Perusal of data compilations given in *Technical Paper* No. 20 of the U.S. Weather Bureau (1960) leaves the impression of variations in the diurnal distribution curves among the Southeast, the Plains States, and the Midwestern States. However, the areal scale employed for this data compilation is much too gross for making firm statements. Others (Armstrong, 1953, and Staff Members of the Severe Local Storm Forecast Center, 1956) have noted the suggestion of spatial variation in the diurnal distribution of tornadoes and have even offered tentative explanations (House, 1963). Yet, little depth of investigation on the degree and spatial scale of the proposed variations can be noted.

This paper describes the methods and results of an investigation of the degree and pattern of spatial variations in the diurnal distribution of tornadoes in the central and eastern United States. The study consists of three interrelated tasks. The first task is to describe objectively the diurnal distribution curves for tornadoes at an areal scale that approximates the first-order synoptic scale. Harmonic analysis provides a relatively simple objective technique for describing histograms of climatological variables (Fitzpatrick, 1964, Horn and Bryson, 1960, and Sabbagh and Bryson, 1962).

Even though much insight is gained by applying the Fourier transformation to the observed frequency distributions, little of substance can be said about spatial patterns or generalized groupings. Thus, our second task is a typologic regionalization of the study area. The regionalization is accomplished by applying cluster analysis to the individual frequency distributions. Three major classes of tornado diurnal-distribution curves result from the cluster analysis. These types are then subdivided into eight subtypes on the basis of secondary maxima.

The concise description and ordering of diurnal-distribution types is important in its own right. However, the ultimate objective should be a rationale for the differences and patterns. The last task undertaken is providing hypotheses and speculations on the physical processes that could account for the previously obtained results. Of the many forces that could be influential, air mass structure, seasonality, land-sea contrasts, preferential origin areas, and squall line propagation are considered. Two facts are immediately clear, however: 1) not all possible causative factors have been considered, and 2) no general explanation can be given.

2. DATA AND STUDY AREA

This investigation is limited to that part of the United States east of the 104th west meridian because it adequately marks the sharp gradient of tornado occurrences in the High Plains. The study area must be subdivided into a number of smaller units that will be the individuals of the subsequent analysis. Initially, a square grid with 100-mi sides (hereafter called the 100-mi grid, squares, cells, etc.) was selected. Each county within the study area was assigned to a cell of the 100-mi grid on a mutually exclusive basis.

For each of these data collection blocks the times of occurrence of all tornadoes from 1916 through 1964 [1] were

[1] The entire period was used because: 1) that quantity of data is required and 2) there is some evidence that the proportion of tornadoes per hour does not change substantially through the record.

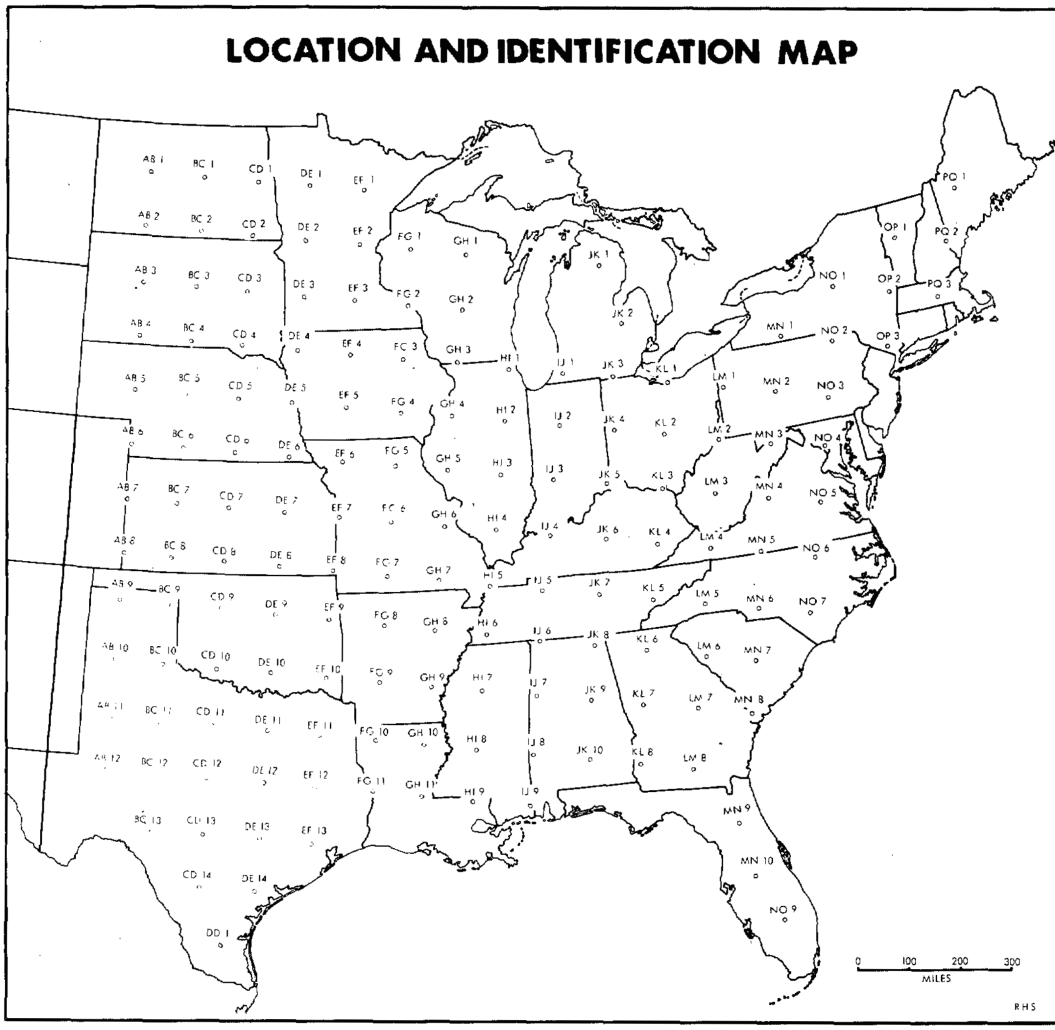

FIGURE 1.—Map of the centers of the analysis areas.

abstracted from published lists (U.S. Weather Bureau, 1916–1934, 1935–1949, 1950–1958, 1959–1964). The times of occurrence are aggregated in 1-hr blocks, because all but 7 to 10 percent of the data record can be used and an acceptable temporal resolution is retained. Thus, the day was broken into 24, 1-hr blocks running from the hour to 59 min past the hour and beginning with 0000 LST. The areal distributions were collapsed to point data taken as valid in the center of each grid cell.

Preliminary analysis of these frequency histograms indicated the 100-mi grid scale contained too few observations per unit for adequate analysis. To compensate, groups of four 100-mi blocks were aggregated into squares having 200-mi sides. To offset the drastic reduction in data points that results from this aggregation, the 200-mi blocks were overlapped by 100 mi in both the north-south and east-west directions. The overlapping procedure has the desirable side effect of spatial and temporal smoothing. The smoothing tends to reduce the amplitude of discontinuities due to difference in the density of observers and differences in reporting practices. Thus, the overlapping procedure is probably closer to reality than the mutually exclusive case. The centers of these 157 data collection units are shown in figure 1 along with a shorthand identification notation for each.

The time of occurrence was then summed over all the 100-mi blocks within each 200-mi block for each hour. The result is an aggregate diurnal distribution histogram for each of the 200-mi grid cells. These frequency distributions are the basic data to be analyzed.

3. DESCRIPTION OF THE DIURNAL DISTRIBUTION OF TORNADOES

HARMONIC ANALYSIS

Derivations of harmonic analysis can be found in a number of standard texts and other material (Brooks, 1953, and Conrad and Pollak, 1962). Therefore, only an outline will be given here. Let $f(x)$ be a function that meets certain conditions of continuity; then,

$$f(x)=a_0+\sum_n(a_n \cos nwt+b_n \sin nwt). \tag{1}$$

Now rewriting (1) as

$$f(x)=a_0+\sum_n A_n \sin(nwt+\beta_n), \tag{2}$$

it can be shown that

$$A_n=(a_n^2+b_n^2)^{1/2} \tag{3}$$

and

$$\beta_n=\tan^{-1}(a_n/b_n). \tag{4}$$

A_n is the amplitude of nth sine wave to approximate $f(x)$, and β_n is the phase angle shift to left of $\pi/2$ of nth wave approximating $f(x)$.

The least-squares approximations (Conrad and Pollak, 1962) of a_n and b_n are

$$a_n=2/k\left(\sum_{i=0}^{k-1} u_i \cos inz\right) \text{ for } n=1, n-1, \tag{5}$$

and

$$b_n=2/k\left(\sum_{i=0}^{k-1} u_i \sin inz\right) \text{ for } n=1, n-1. \tag{6}$$

In (5) and (6) the notation is:

a_n and b_n=Fourier coefficients,
n=the order of the harmonic,
u=deviations from the mean,
k=number of discrete time periods,
$z=2\pi/k$.

Since k is even, (5) and (6) have to be modified by multiplying by (½) for $n = max$.

The numerical values for the amplitudes depend on the size of the observed distribution. Thus, comparison of the importance of common harmonics between individual frequency distributions cannot be based on amplitudes. However, the variance in each harmonic is $(½)A_n^2$. The total variance of actual distribution is:

$$\sigma^2=(\sum_k(X_k-\overline{X})^2/k-1.$$

The ratio, $A_n^2/2\sigma^2$ is often referred to as the reduction of variance (RV) by the nth harmonic. We shall express RV as a percentage and use it as a measure of the absolute and relative importance of any harmonic component.

After correction for quadrant, the phase angles can be expressed in time units. To make the conversion we shall use:

$$t_{max}=\begin{cases}[(\pi/2-\beta_n)/n]/Z & \text{for } 0\leq\beta_n\leq\pi/2\\ [(5\pi/2-\beta_n)/n]z & \text{for } \pi/2\leq\beta_n\leq 2\pi.\end{cases} \tag{7}$$

The time in hours is for the first maximum of each harmonic.

The n, RV, and time values completely specify each frequency histogram and serve as an objective description. Twelve harmonics were computed for each individual. We must now turn our attention to interpretation of the harmonic components in terms of diurnal distribution of tornadoes and determine if spatial variation in the shape of the observed curves is indicated.

CENTRAL TENDENCY MEASURES

Interpretation of the harmonic analysis is materially aided if some notions of the curve shapes and data availability are obtained first. The mean and the coefficient of variation are important general parameters.

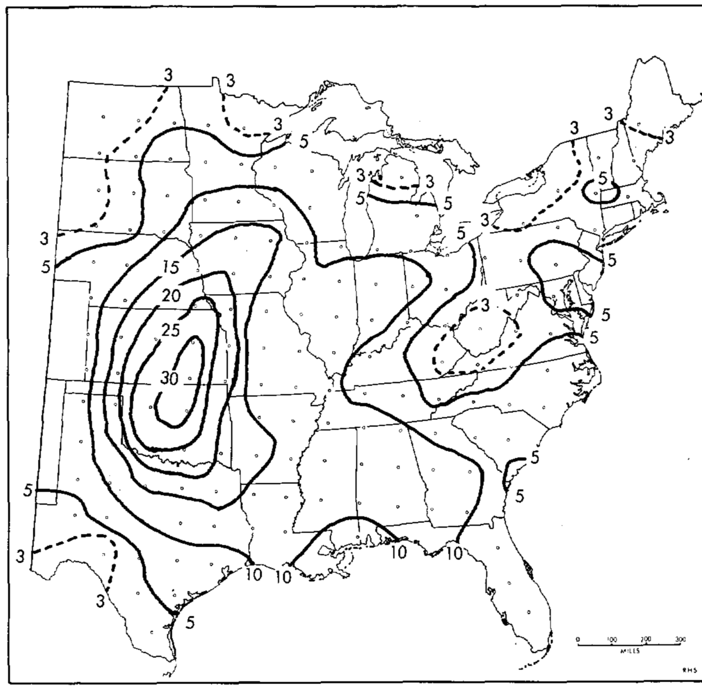

FIGURE 2.—Map showing the mean number of tornadoes per hour for the period 1916–1964.

Figure 2 shows the mean number of tornadoes per hour aggregated from 1916 through 1964. Formally, the mean is defined as:

$$\overline{X}=\sum_{i,j} X_{ij}/24 \tag{8}$$

where $i=1, 2, \ldots, n, \ldots$, the number of days in the period 1916 through 1964, and $j=1, 2, \ldots, 24$, the number of hours per day. It is apparent that densities are not accurately portrayed in figure 2 but the relative values are correct and the amount of data available for analysis is clearly shown.

The general pattern in figure 2 is as one would expect. "Tornado alley," from northern Texas to southwestern Iowa, is outlined approximately by the isopleth of 20 tornadoes per hour. Away from this centroid of tornadic activity, the values decrease, more sharply to the west, north, and south, and become rather even to the east after a sharp decrease in Missouri.

Of greater importance are the areas with a mean less than three tornadoes per hour. These are data-deficient areas. As an approximation, harmonic analysis requires observations numbering at least 6 times the order of the highest harmonic. Thus, 72 or $\overline{X}\geq 3$ observations are required in this study to have much assurance that the results of the harmonic analysis are reliable. Six areas are indicated as data-poor on figure 2. These are: 1) western North and South Dakota, 2) the arrowhead of Minnesota, 3) northern Michigan, 4) northern New England and New York, 5) central Appalachian Plateau, and 6) southwestern and southern Texas. These are considered outside the context of harmonic analysis later in this paper.

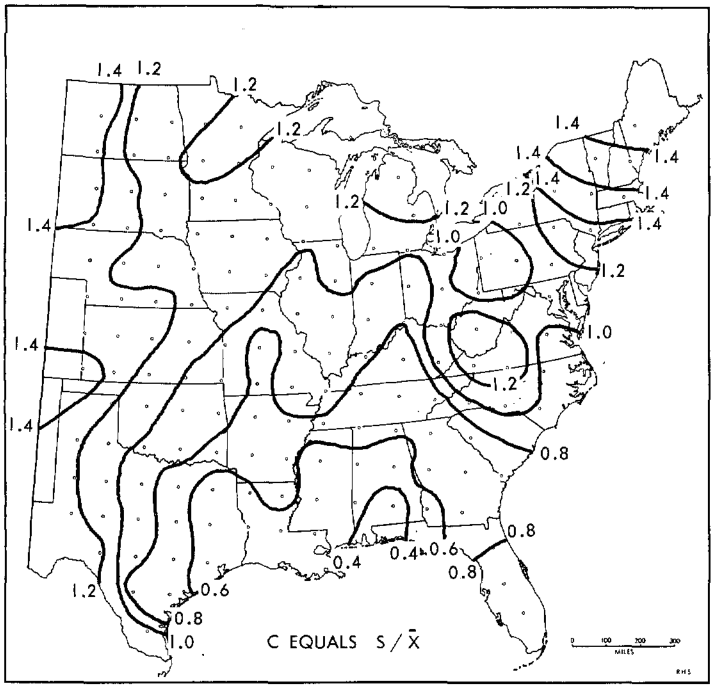

FIGURE 3.—Map of the spatial variation in the coefficient of variation. See text for the importance of the values.

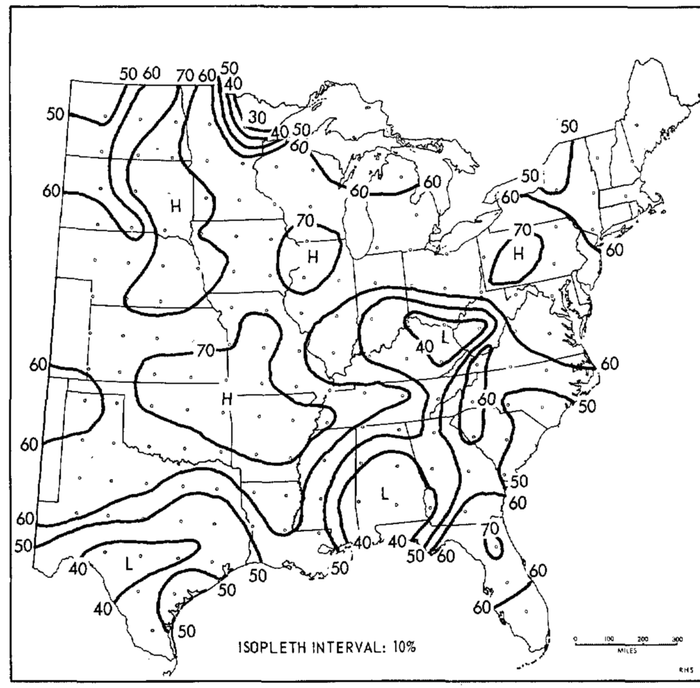

FIGURE 4.—Map showing the percentage reduction of variance contributed by the 1st harmonic.

The coefficient of variation is defined as the root-mean-square (*rms*) variance divided by the mean. Thus, C is a size-independent measure of dispersion around the mean. C varies between zero when the *rms* variance approaches zero and $(n-1)^{1/2}$ when the distribution consists of $(n-1)$ zero values and one other value of any magnitude (Hastings, 1965). It can be shown that C cannot be greater than one for a zero-bounded, normal distribution. Thus, as C tends away from one towards its upper bound, the distribution becomes more spike like or leptokurtic.[2] Conversely, as C approaches zero the curve shape approaches a horizontal line and becomes more platykurtic. Between these two extremes, at values less than one, a distribution shape of nearly normal character exists.

By applying these interpretations of the coefficient of variation to the values shown on figure 3, a general idea of distribution shapes over the whole of the study area emerges. Most of the Plains States, the upper Midwest, the Middle Atlantic States, and New England have distinct tendencies toward leptokurtic distributions. On the other hand most of east Texas, Louisiana, Mississippi, and Alabama tend toward platykurtic distributions. Between, nearly normal-shaped distributions occur. As we shall see shortly, these remarks are critical for a reasonable interpretation of the harmonic components.

THE FIRST HARMONIC

The 1st harmonic indicates the propensity of the observed distribution for a one-cycle per day shape. The degree to which a frequency 1 sine curve fits the observed data is given by the percentage variance reduction by the 1st harmonic. Figure 4 clearly indicates that the 1st harmonic is a good first approximation of the observed distributions for fully three-quarters of the study area. The best fit for the 1st harmonic occurs in the areas marked by an H on figure 4. The RV is 70 percent or greater for these regions. The region of substantial reduction of variance by the 1st harmonic (60 percent or greater) includes nearly all of the northern and central Plains, the Mississippi Valley, the Lower Great Lakes, and the Middle Atlantic States.

Low RV values by the 1st harmonic are localized in southern Texas, the Gulf Coast of Mississippi and Alabama, and the middle Ohio Valley, with lowest values occurring in south-central Mississippi. The arrowhead portion of Minnesota also has very low (less than 30 percent) 1st harmonic RV. However, data insufficiencies make it impossible to accept the values.

Few generalizations can be made about observed curve shapes from the 1st harmonic alone. It is safe to say that at least those areas with 50-percent or more variance "explained" by the 1st harmonic are unimaximal-unimininal in broad outline. However, the curve detail is not adequately given even for those areas with very high RV by the 1st harmonic. Further, one is not sure whether areas of poor fit result from the lack of a diurnal component, unequally spaced maxima and minima, secondary maxima, and/or other variabilities. The other harmonic components must be interpreted in conjunction with the 1st harmonic if any insight is to be gained.

The time of the maxima of the daily cycle of tornado activity is shown on figure 5. The isochrones indicate two

[2] I use the terms platykurtosis and leptokurtosis to conjure a picture of "uniform" and "peaked" distributions, respectively. This terminology is not absolutely correct but the allegorical worth seems to prevail here.

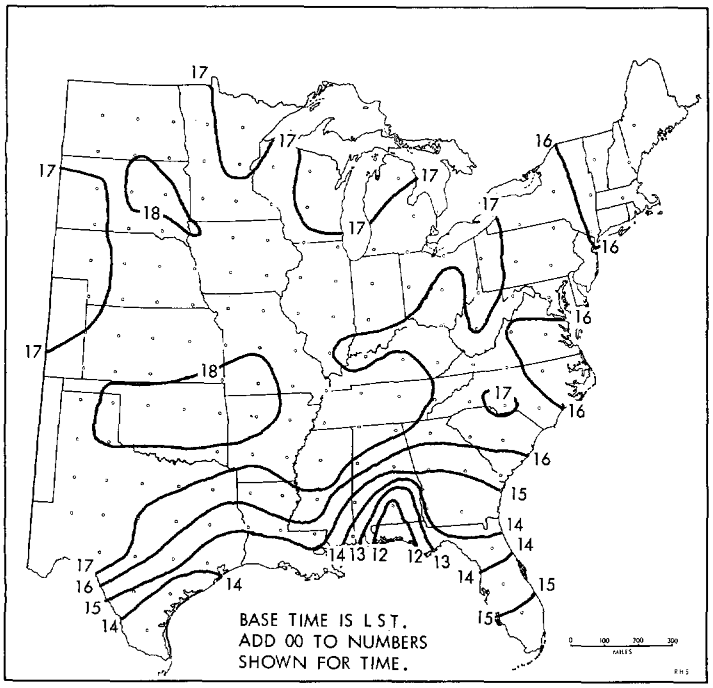

FIGURE 5.—Map of the time of maximum of the 1st harmonic.

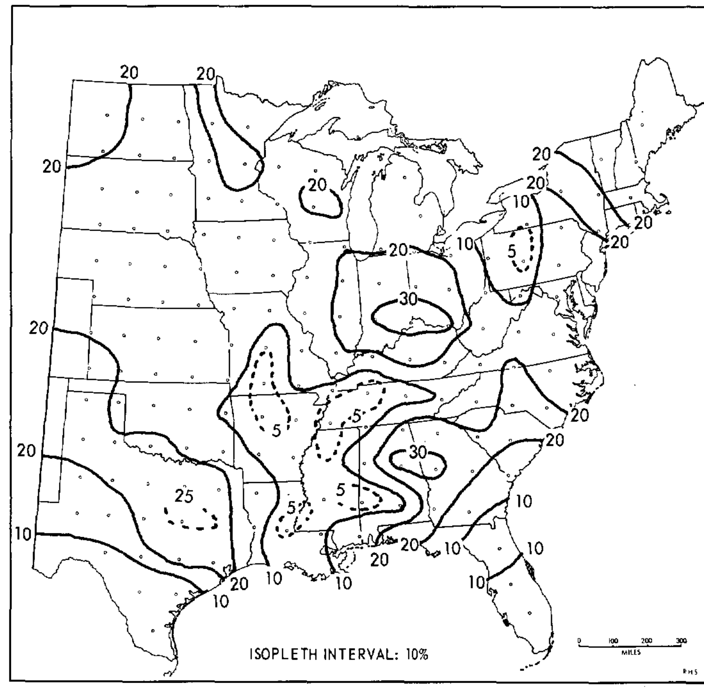

FIGURE 6.—Spatial distribution of the percentage of variance "accounted for" by the 2d harmonic.

patterns. The first pattern is a west to east change. The hour of maximum in the far west of the study area is late afternoon (1600 LST). The hour of maximum becomes later in an eastward direction reaching 1800 to 1900 LST in the eastern Plains. The trend then reverses with the times of maxima becoming earlier until a midafternoon maximum (1500 LST) is reached in New England. This pattern is in agreement with most other descriptions.

Near the Gulf Coast a second pattern is recognizable. Here the times quickly become earlier as the coast is approached. In the immediate coastal regions, midday and early afternoon apparent maxima are indicated. However, it must be remembered that the importance of the 1st harmonic is relatively low here and that curve shapes other than the single maximum types are probable.

THE SECOND HARMONIC

The 2d harmonic reduction of variance maximizes in three areas (see fig. 6). These are: 1) eastern Mississippi and western Georgia, 2) eastern Texas, and 3) the middle Ohio Valley. These three areas have lower 1st harmonic variance reduction. One cannot, however, conclude that a strong semidiurnal-observed curve shape exists.

The Lower Mississippi Valley, western Pennsylvania, and northern Florida have very low variance reduction by the 2d harmonic. We may conclude that little semidiurnal variation is indicated for these regions. It should be recalled that relatively substantial 1st harmonic *RV* also occurs.

Intermediate values of 2d harmonic *RV* (10 to 20 percent) cover much of the study area. The interesting aspect is the correspondence between intermediate 2d harmonic *RV* values and large 1st harmonic *RV* values. However, interpretation of the meaning of the 2d harmonic is best accomplished by comparing the phase angles for the 1st and 2d harmonics.

TYPES OF CURVE SHAPES INDICATED BY FIRST AND SECOND HARMONICS

The curve shapes for much of the study area can be generalized from the first two harmonic components. However, the interpretation must be done for both together taking account of several functions that each component may perform. One approach is to compare the times of maxima between the 1st harmonic and the second maximum of the 2d harmonic. Figure 7 is an isopleth map of the differences in time in hours. Negative values indicate that the second maximum of the 2d harmonic occurs earlier than the 1st harmonic maximum and conversely.

There are three items of interest shown on figure 7. First, over much of the study area the 1st and 2d harmonics are in phase. This is indicated by less than 1-hr difference in the maxima times. Second, substantial difference exists along the Gulf Coast. And third, small phase angle differences occur in the mid-Mississippi Valley, although only the southern Illinois portion has 2d harmonic *RV* values large enough to ascribe any importance to the difference.

If the phase angle differences are combined with the *RV* values for the 1st and 2d harmonics, then several important combinations are noted. The first occurs in the central and northern Great Plains, the upper Midwest, parts of the Middle Atlantic States, and New England, where the time difference is small, the 1st harmonic *RV* relatively large, and the 2d harmonic *RV* intermediate in value. This combination can be interpreted as an indication of a one-peak distribution that is at least somewhat leptokurtic, as illustrated by the graph for data point DE6 in figure 8.

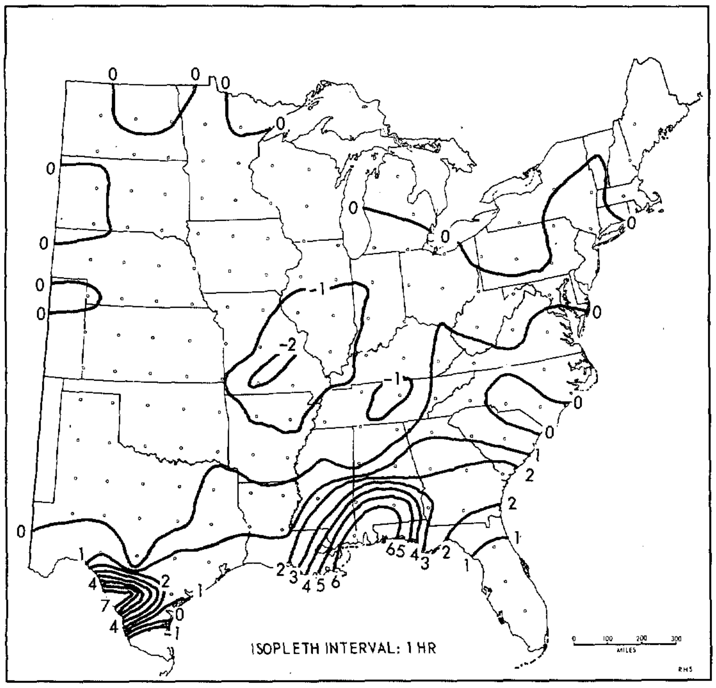

FIGURE 7.—Map of the difference in hours between the maximum of the 1st harmonic and the second maximum of the 2d harmonic.

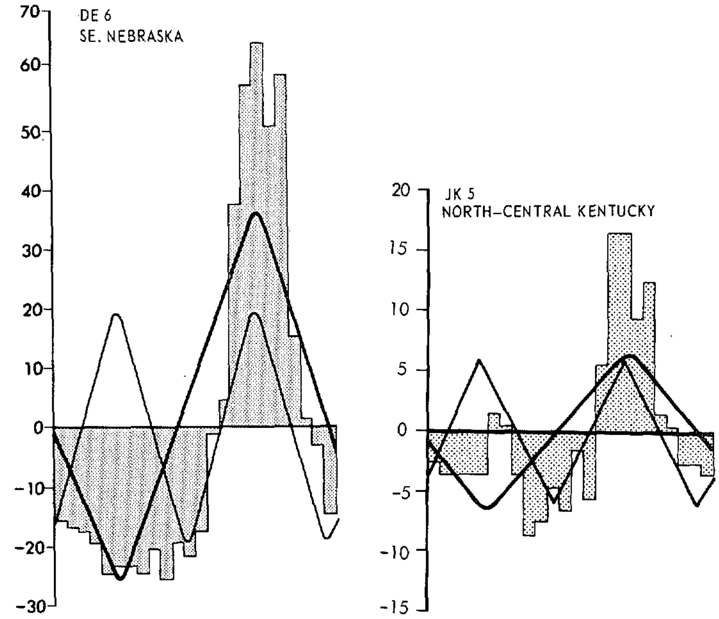

FIGURE 8.—Graph illustrating the functions that the 1st and 2d harmonics can perform in describing the observed frequency distributions. The distribution is given as deviations from the mean by hour. The solid curves are the harmonics. See text for discussion.

As is seen, the maximum is stronger than the minimum. The 1st harmonic must be reinforced by the 2d harmonic to increase the amplitude of the primary maximum and reduce the amplitude of primary minimum. Thus, one 2d harmonic maximum occurs at the time of the 1st harmonic maximum and one at the time of the 1st harmonic minimum. The two minima of the 2d harmonic occur at the inflection points of the 1st harmonic curve. The effect is to shrink the time span for the maximum and stretch the span of the minimum which is necessary for a leptokurtic distribution.

Of the areas with relatively high RV by the 2d harmonic, the one centered in northern Kentucky has small differences in the times of maxima of the 1st and 2d harmonics. The graph for JK5 in figure 8 illustrates the relationships. Note that the primary maximum is too large for 1st harmonic representation and that a secondary maximum occurs displaced 12 hr from the primary maximum. For this reason the RV value is higher than the previous case but no phase angle difference is noted.

In Mississippi, Alabama, and Georgia there are areas that have both relatively high variance reduction by the 2d harmonic and substantial time differences between the 1st and 2d harmonics. In these areas the diurnal cycle is relatively weak, and a semidiurnal cycle is required. However, it is not possible to say whether the frequency-2 periodicity is dominant or part of a more complex situation.

THE THIRD HARMONIC

The reduction of variance by the 3d harmonic is portrayed in figure 9. The center of the largest 3d harmonic

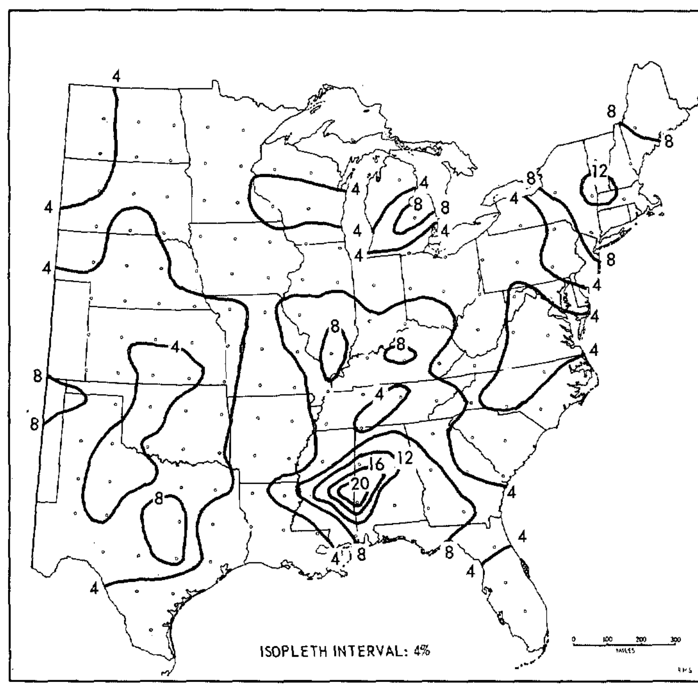

FIGURE 9.—Map of the percent reduction of variance of the 3d harmonic.

variance reduction is in east-central Alabama. The strict interpretation is a strong tendency toward a trimodal distribution superimposed on an almost equally strong diurnal cycle. The phase angle for the 3d harmonic indicates maxima near 0200 LST, 1000 LST, and 1800 LST, which when compared with the 1st harmonic maximum reveals

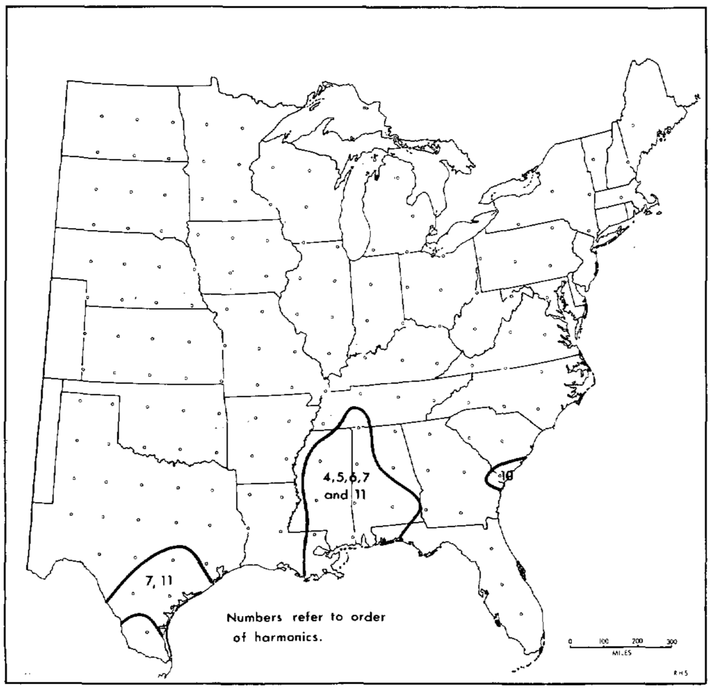

FIGURE 10.—Map of the areas where harmonics of order 4 or greater are important.

that reinforcement is not the function performed. Rather, substantial nonperiodic variability seems to be indicated.

In New England the 3d harmonic RV values are also large. However, a 3d harmonic maximum corresponds to the 1st harmonic maximum, and this component is a reinforcement of a strongly leptokurtic distribution. It will be recalled that the coefficeint of variation is also large in New England, confirming the interpretation of leptokurtosis.

HIGHER ORDER HARMONICS

Maximization of the 4th through 12th harmonics is highly localized; therefore, it is more profitable to discuss them on an areal basis. Figure 10 gives on outline of the areas where the higher order harmonics are relatively important, as well as the specific harmonics involved. The Gulf Coast States experience relative maxima for the 4th, 5th, 6th, 7th, and 11th harmonics, with the last being most widespread. The 7th and 11th harmonics appear important along the Gulf Coast of southern Texas, while the 10th harmonic has a maximum of variance reduction along the Atlantic Coast of Georgia and South Carolina.

Interpretation of these higher order harmonics is difficult at best. It is not possible to think of them as periodicities because their high frequency is difficult to perceive in terms of tornado processes. It seems that they can best be regarded as components required to account for hour-to-hour variability in the observed distributions. It is convenient to think of this variability as random, as opposed to the highly organized distributions common over the rest of the study area.

4. TYPOLOGIC REGIONALIZATION OF THE DIURNAL DISTRIBUTION OF TORNADOES

INTRODUCTION

Although a feeling for the direction and magnitude of spatial variation of the diurnal distribution of tornadoes is obtained from harmonic analysis, the general distribution types and their areal arrangement is far from clear. It is necessary to generalize the harmonic analysis so that some degree of order and conciseness is brought to the results.

CLUSTER ANALYSIS

Cluster analysis is an objective polythetic classification scheme based on the overall similarity between the individuals. The overall similarity is assessed by one of several possible coefficients of association, and the cluster analysis is carried out by one of several linkage conventions. However, it is not possible to discuss the various possible combinations in this paper. Therefore, the reader is referred to the work by Sokal and Sneath (1963), the basic source.

The 12 reduction-of-variance values in percent and the 12 phase angles expressed in radians are the 24 characters used to describe each individual (frequency distribution). The index of similarity used is the Pearson product-moment correlation coefficient, i.e., $r=\sigma_{xy}/\sigma_x\sigma_y$, because it is especially suited for representing similarity of curve shape (Rohlf and Sokal, 1965).

The complete linkage criteria for cluster analysis was used because the resultant clusters tend toward spheres in n-space rather than hierarchies, and the separation between groups of comparatively highly similar individuals is accentuated. The complete linkage criteria are as follows. The mutually highest correlated pairs are chosen as initial nuclei of clusters. At successively lower correlation levels, individuals are linked, clusters coalesced, and individuals added to clusters if and only if each individual to be involved in the linkage correlates with every other individual at or above the minimum correlation level of the particular clustering round. This process is continued until all individuals coalesce into a single class.

RESULTS OF THE CLUSTER ANALYSIS

The output of cluster analysis is most intelligibly represented via a dendrogram. It is not possible to show the entire dendrogram in a single figure; however, a schematic version is given in figure 11. In this figure the first and last individuals for each of four major clusters are shown, along with the linkages between these clusters. It is apparent from a first glance that four discrete groups exist.

Closer inspection of the dendrogram reveals that some profitable arrangement is possible. The first group is small and contains mostly marginal or data-poor areas. Therefore, this group was eliminated and the individuals assigned to the other three groups on the basis of visual

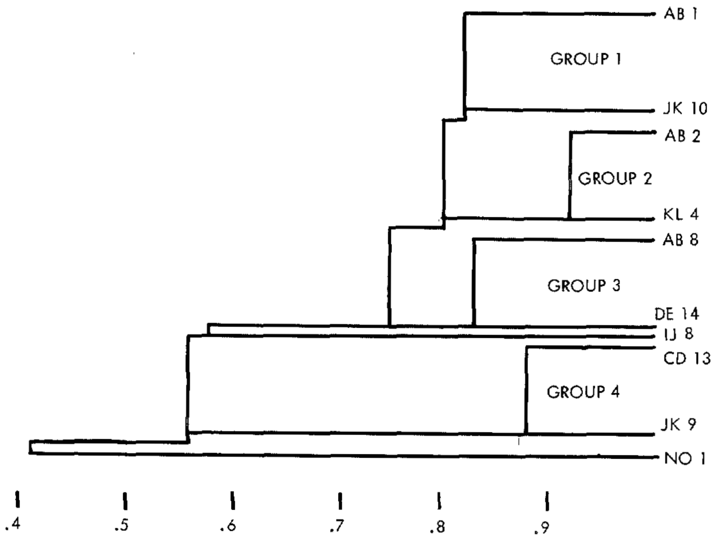

FIGURE 11.—Schematic diagram of the results of the cluster analysis. The correlation values are shown along the bottom and the intergroup linkages by the solid lines.

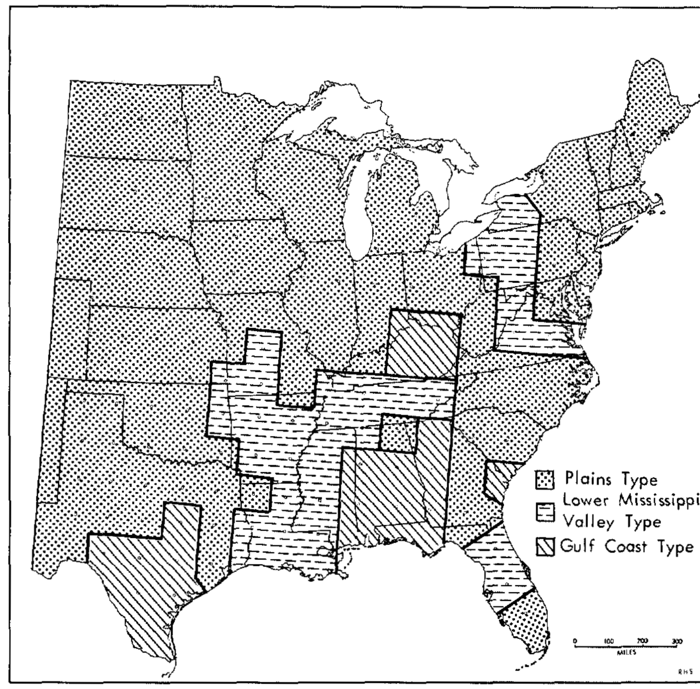

FIGURE 12.—Map of the cluster analysis of the diurnal distribution of tornadoes.

appearance. Further, three other changes were made where the individuals could easily have gone to either group.

The results of the cluster analysis are shown spatially in figure 12, where the groups have been given descriptive names. Group 2 is the Plains Type distribution, group 3 the Lower Mississippi Valley Type distribution, and group 4 the Gulf Coast Type distribution.

The characteristics that set these three diurnal distribution types apart can be seen in the results of the harmonic analysis. Comparison of figure 4 with figure 12 reveals that the Plains and Lower Mississippi Valley distributions are areas of relatively high 1st harmonic RV values, while the Gulf Coast distribution has low variance reduction by the 1st harmonic. It also appears that the Lower Mississippi Valley Type has the highest RV by the 1st harmonic. Of particular interest are the southward bulge of relatively high RV values in Louisiana and the eastward bulge in Tennessee, which correspond to Lower Mississippi Valley Type.

Comparison of figure 6 with figure 12 shows the influence of the 2d harmonic RV as a differentiating character. The areas of low 2d harmonic RV are coincident with the Lower Mississippi Valley Type, while the Gulf Coast Type corresponds in part with the high values of the 2d harmonic reduction of variance. The Plains Type distribution has intermediate values that represent the reinforcement function cited earlier.

The 3d harmonic enters into the classification in two ways. First, high 3d harmonic RV values correspond to those areas of the Gulf Coast Type not having high 2d harmonic variance reduction. Second, the 3d harmonic serves as a reinforcement for the strongly leptokurtic Plains Type in New England.

The higher order harmonics tend to maximize their importance in the Gulf Coast Type distribution. There is some spillover into the Lower Mississippi Valley Type, which corresponds to one of the subtypes, as we shall see shortly.

Combining the above comments with the discussion of the coefficient of variability, it is possible to obtain a clear picture of main characteristics of the distribution curve types. The Plains Type is more or less leptokurtic and requires the 1st harmonic, the 2d harmonic, and at times the 3d harmonic to produce the general curve shape. The Lower Mississippi Valley Type requires only the 1st harmonic to portray the general shape because of the more equal amplitudes of the maximum and minimum. Finally, the Gulf Coast Type requires the 1st, 2d and/or 3d, and one or more higher order harmonics to approximate the observed distributions. This is indicative of a multimaximal, platykurtic distribution.

The above classification scheme may be objected to because there is no internal way of deciding whether the clusters chosen represent different populations. This decision is critical in geographic work for it is apparent that the regionalization does not exist if it is likely that the groups came from the same parent population.

Multivariate, linear discriminant analysis provides one way of investigating the probability that groups in a classification come from the same population. Primary interest, for this application, is focused on Mahalanobis' Generalized Distance (D^2) and its statistical significance. D^2 (Davis and Sampsen, 1966) is obtained by using:

$$D^2 = \sum_i \lambda_i \overline{\Delta X}_i. \tag{9}$$

In equation (9) the λ's are the coefficients from the linear discriminant function (plane) separating the two groups in hyper-space and the $\overline{\Delta X}$'s are distances between the group means of each variable used to characterize an

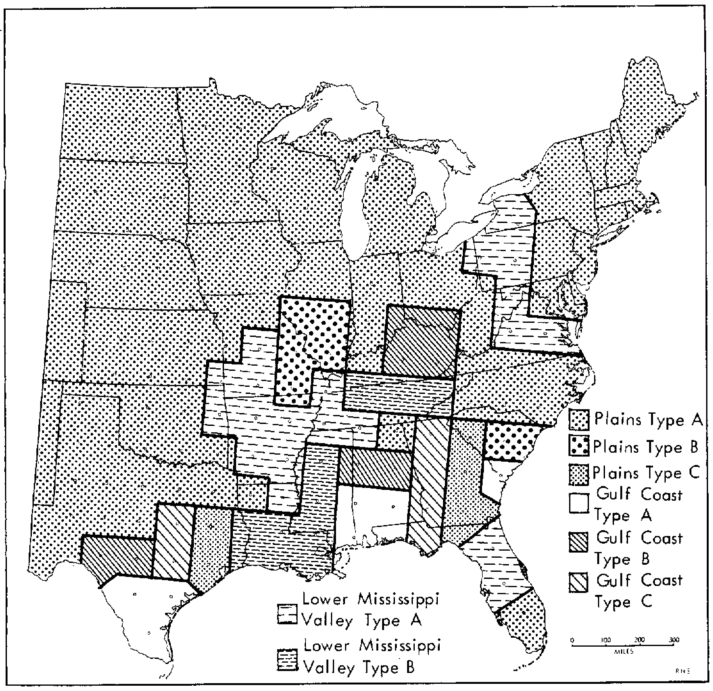

FIGURE 13.—Regional pattern of the diurnal distribution of tornadoes.

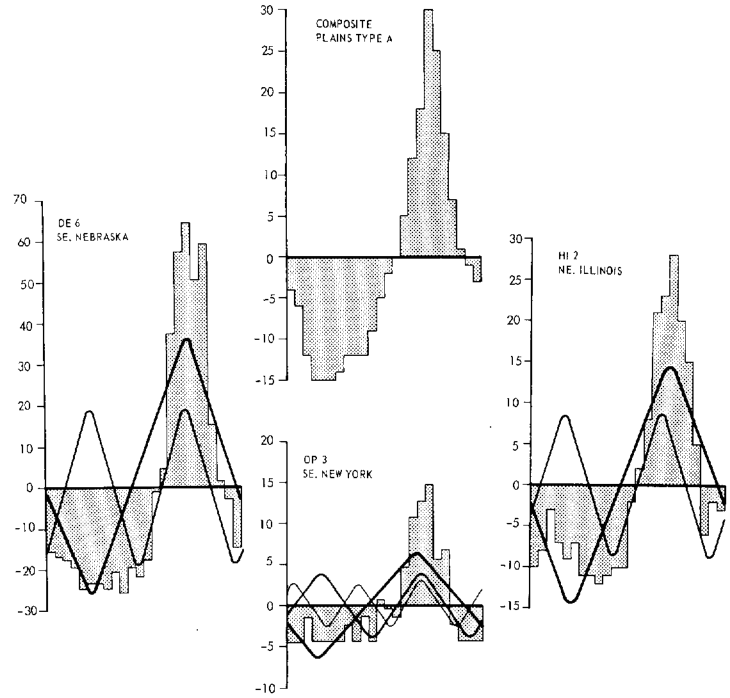

FIGURE 14.—Composite and three observed frequency distributions of the Plains Type A. Note the leptokurtic form.

observation. The i's index these variables and the summation is over all the variables used in the analysis. The 12 RV and 12 phase angles are the variables that characterize each observation (frequency distribution). Thus, we are determining the "average" distance in n-space between two preselected groups. The statistical significance of this generalized distance is given by Davis and Sampsen (1966):

$$F=[n_1n_2/(n_1+n_2-2)][n_1+n_2-K-1)/K][D^2] \qquad (10)$$

with K and (n_1+n_2-K-1) degrees of freedom. In equation (10), n_1 is the number of observations in group 1; n_2 is the number of observations in group 2; and K is the number of variables.

Equations (9) and (10) were applied to each combination of the three groups obtained through cluster analysis, i.e., Plains vs. Lower Mississippi Valley, Plains vs. Gulf Coast, and Lower Mississippi Valley vs. Gulf Coast. In all cases the F-ratio was significant at the $P=.001$ level indicating that it is not very likely that the three groups come from the same population. It may be concluded that the classification derived from cluster analysis is a good classification although it may not be optimal.

SUBDIVISION OF THE FUNDAMENTAL TYPES

Although the three diurnal-distribution types revealed by cluster analysis encompass the main characteristic features, inspection of the observed data clearly shows important within-type variations. A first attempt at detailing the within class variance was made by applying cluster analysis to the individual types after standardization of the characters. However, little success was evident in the results. It was, then, decided to subdivide on the basis of secondary maxima.

A secondary maximum is defined as a relative maximum whose amplitude is equal to or greater than the mean number of tornadoes per hour. Further, the secondary maxima are divided into early morning (0100 to 0500 LST) and late morning (0600 to 1100 LST) types. The broad cluster analysis distribution types were subdivided into eight groups using these differentiating characteristics. These eight subtypes are shown areally in figure 13.

The Plains distribution is divided into three groups—Type A with no secondary maximum, Type B with an early morning secondary maximum, and Type C with a late morning maximum. The Plains Type A distribution is the "modal" type for tornado alley and the aggregate of the whole United States. As can be seen in figure 14, the afternoon maximum is very sharp and only a few hours encompass the height of tornadic activity. The Plains Type B distribution, as shown in figure 15, is very similar to the Type A save for early morning secondary maximum. The secondary maximum is relatively weak in amplitude but occurs at almost the same time over a considerable area. In contrast, the Plains Type C has a late morning secondary maximum of considerable amplitude but covers relatively little area (see fig. 16).

At the other end of the sprectum is the Gulf Coast distribution. This grouping is also divided into three subtypes. Figure 17 gives the observed frequency distributions of the Gulf Coast Type A. The most obvious and important characteristic is the lack of any well-defined primary maximum and minimum. The multimaximal curve shows no recognizable periodicity. Thus, the Fourier representation must be comparatively complex. Clearly, this type is very distinctive.

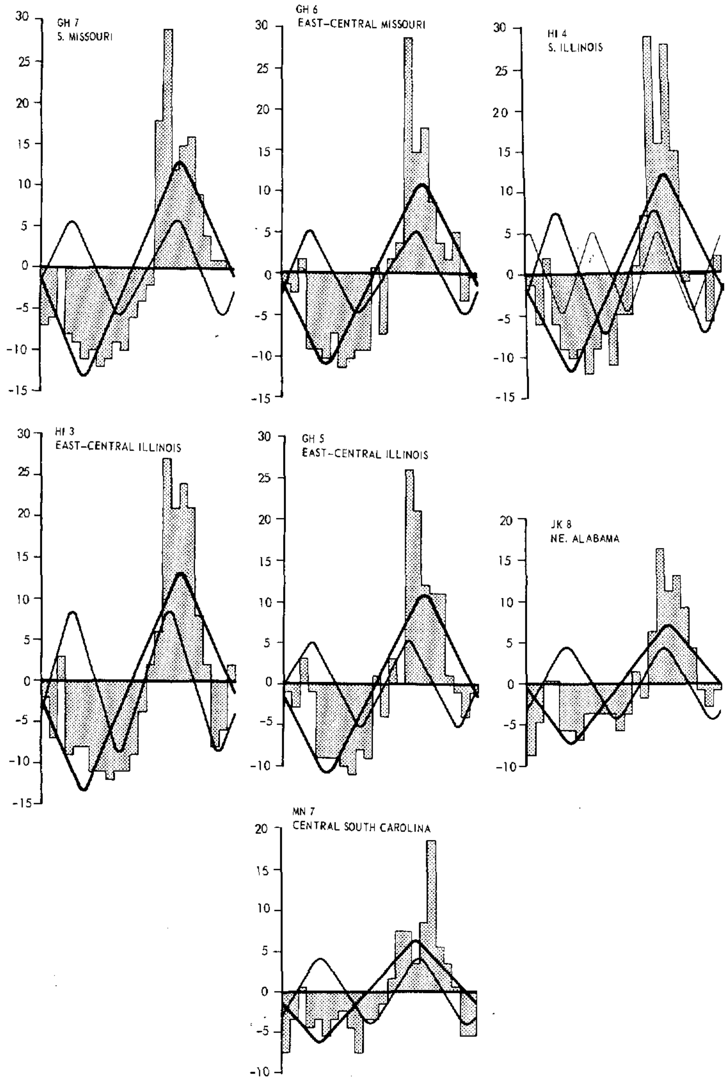

FIGURE 15.—Observed Plains Type B frequency distributions. Note the early morning secondary maxima.

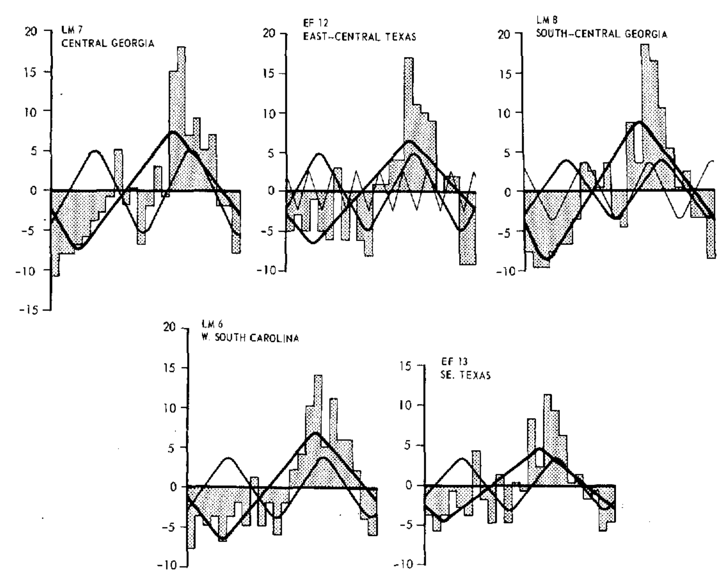

FIGURE 16.—Observed Plains Type C distributions. Note the late morning secondary maxima.

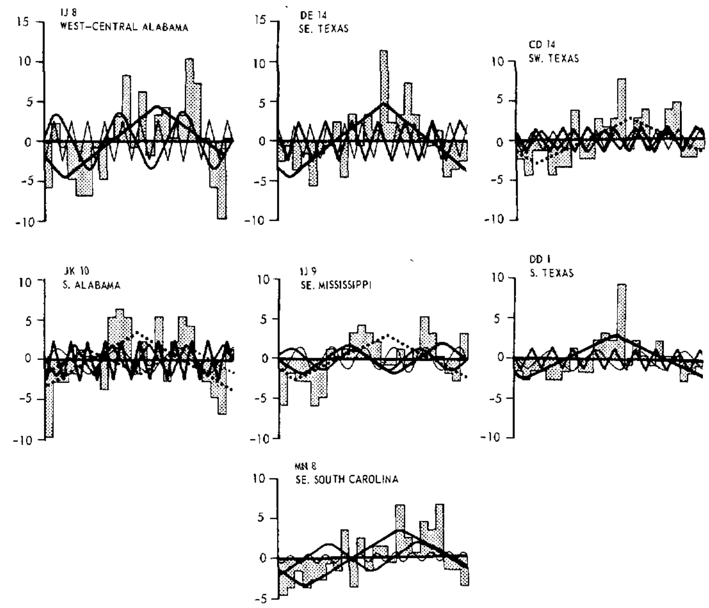

FIGURE 17.—Observed distribution for the Gulf Coast Type A. The multimaximal form is easily seen.

The Gulf Coast Types B and C differ from the Gulf Coast Type A by virtue of a primary maximum. However, they also have a strong early and late morning secondary maxima respectively. In addition, as shown in figures 18 and 19, there is a great degree of interhour variability, which contrasts with the smooth increase and decreases typical of the other types.

The Lower Mississippi Valley distribution can be broken into two groups only. The Lower Mississippi Valley Type A, as shown in figure 20, is very similar to the Plains Type A. The main differentiating feature is the less leptokurtic distribution, i.e., the maximum and minimum are of equal amplitude and approximately equally spaced. In other respects, little difference between the Plains and LMV Type A distribution can be noted.

A tendency toward the Gulf Coast distribution can be seen in figure 21, which shows the typical Lower Mississippi Valley Type B distribution. Note that the basic normal distribution form remains but that the interhourly variability during the morning hours is similar to the Gulf Coast distribution. In my opinion the Lower Mississippi Valley types are transitional between the Plains and the Gulf Coast distributions. Yet, the LMV distributions seem sufficiently distinctive to merit their own classes.

5. DYNAMIC CLIMATOLOGY OF THE DIURNAL DISTRIBUTION OF TORNADOES

INTRODUCTION

The types of diurnal distribution curves and their spatial arrangement as developed in the preceding sections are important in their own right. Yet, it should be

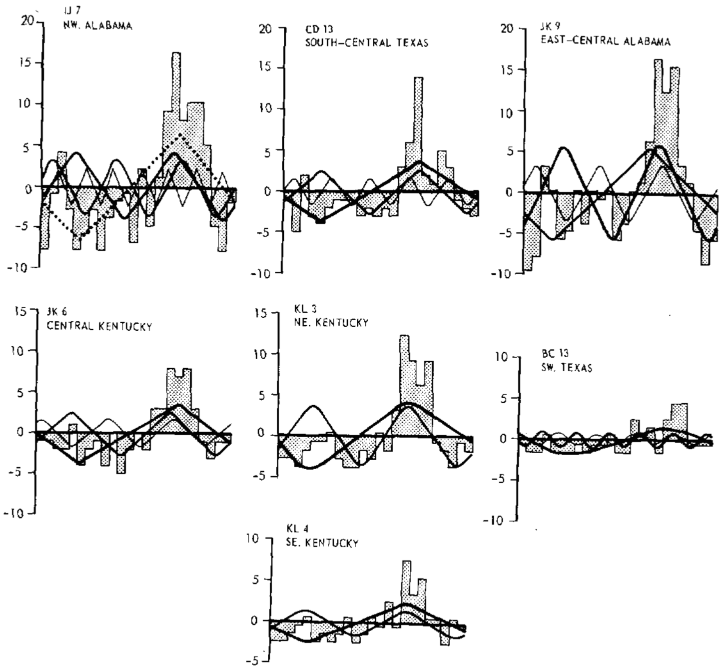

FIGURE 18.—Observed Gulf Coast Type B distributions. Note the early morning secondary maxima and large interhourly variation.

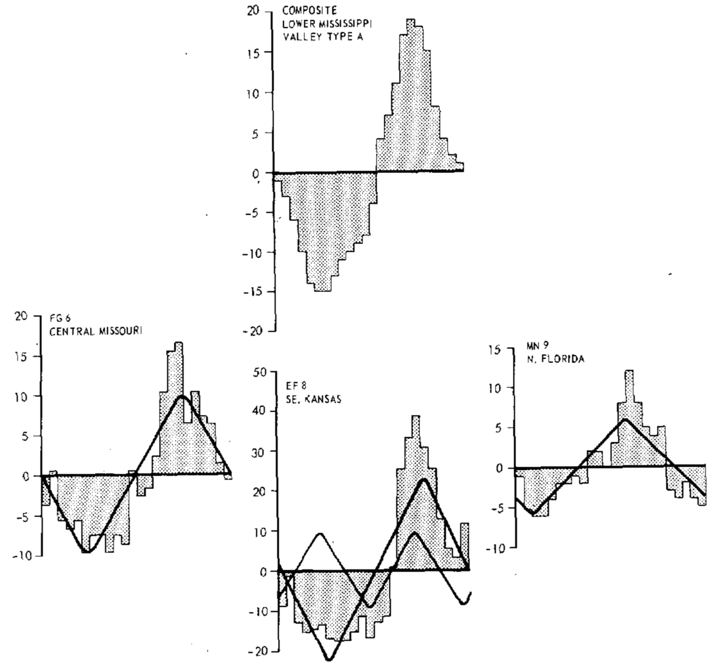

FIGURE 20.—Composite and three observed Lower Mississippi Valley Type A distributions. Note the more symmetrical curve shapes.

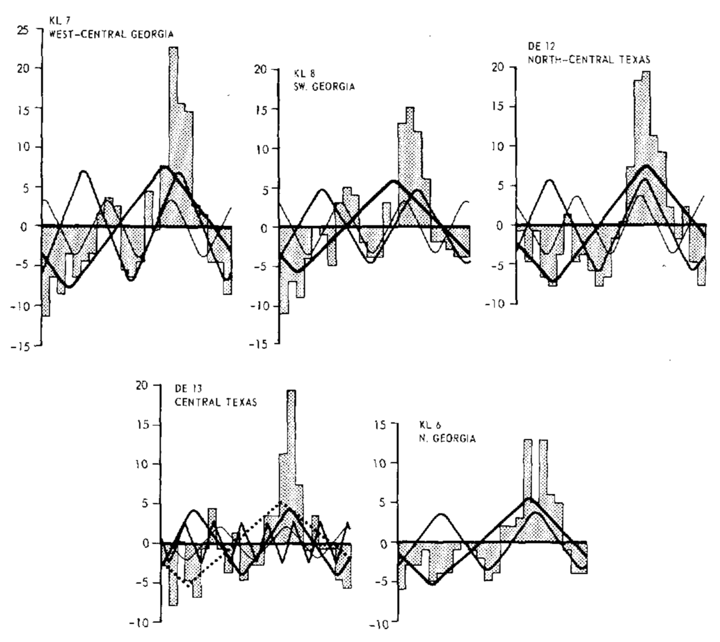

FIGURE 19.—Observed Gulf Coast Type C distributions.

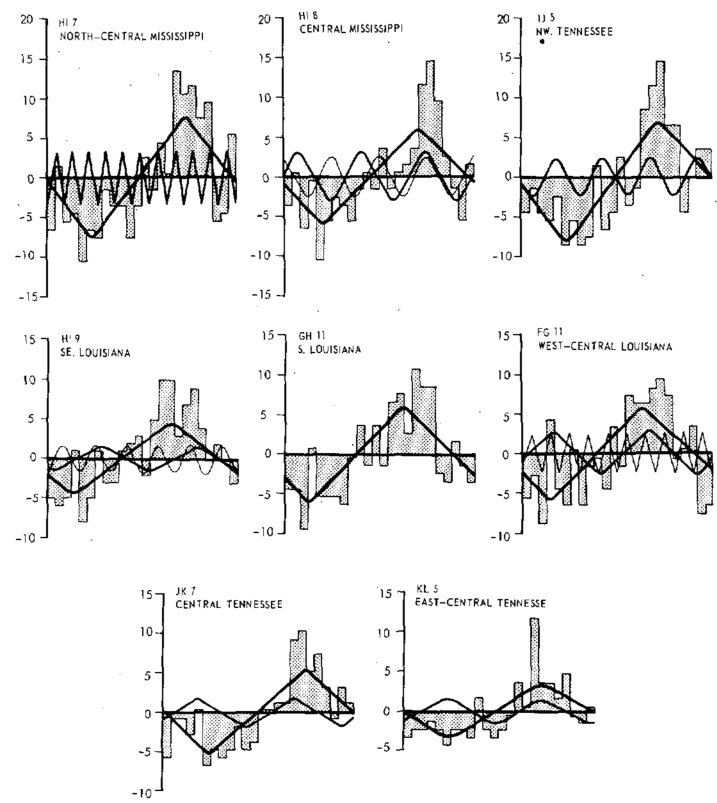

FIGURE 21.—Lower Mississippi Valley Type B distributions. The secondary maxima are clearly shown.

remembered that an explanation for the results is equally important. In the following paragraphs a limited, first attempt at explaining the variations in the diurnal distribution of tornadoes will be given.

The major problem in trying to explain or rationalize the areal pattern shown in figure 13 is the lack of knowledge about the pertinent processes involved. At the present time there is no explanation for the causes of tornadoes. Therefore, the approach must be made through a consideration of the intense convective systems with which tornadoes are usually associated.

THERMODYNAMICS AND DYNAMICS

In accounting for the occurrence of severe thunderstorms, both thermodynamic and dynamic considerations are important. The relationship is by no means unique however, for, as Foster (1964) points out, tornadoes have occurred in the range from strong dynamics and weak thermodynamics to weak dynamics and strong thermodynamics.

With regard to thermodynamics, researchers have isolated four precedent air mass-stability structures common in tornado situations (Staff Members of the Severe Local Storm Forecast Center, 1956). The Type I structure, the most common and well-known, is potentially unstable and is ambient in the central United States during most of the spring and summer. In the southeastern United States during the summer, the Type II air mass structure is dominant. This structure is characterized by a rather deep moist layer, conditional instability, and the lack of convective instability. In contrast to the Type II air mass, the Type IV is relatively dry in depth but very nearly dry adiabatic in environment lapse rate. The Type IV is usually confined to the High Plains during the summer months. The final air mass structure, the Type III, is quite rare and occurs only in a few cases in the northeast.

Although thermodynamic conditions are necessary, they are by no means sufficient. Some dynamic process is required, usually in the form of an approaching shortwave trough. Dynamic lifting is most necessary when the air mass structure contains one or more relatively stable layers, as is typical in the Type I structure. Even though dynamic lifting is, as Beebe (1958) has shown, quite effective in removing the stable layers, some trigger mechanism such as heating, low-level convergence, frontal lifting, or topographic lifting is often needed to set off convection. The question then is how combinations of thermodynamic and dynamic conditions might effect the diurnal distribution of tornadoes.

Initially, it is useful to compare and contrast the Plains Type and Gulf Coast Type distributions. In the Plains Type of interior location at least, the typical tornadic air masses are the Type I and to a lesser extent the Type IV. Both of these require diurnal heating to encourage convection, especially the Type IV. As a result we should expect to find a tendency for a sharp afternoon maximum of tornadic activity, as indeed we do.

In the Gulf Coast Type distribution, tornadoes usually occur with the Type I air mass during the winter and early spring and the Type II during the late spring and early summer. Thus, it should be anticipated that an afternoon bias occurs in the former "season" and more variability in the latter when the air mass structure is much less stable.

Figure 22 shows the diurnal distribution of tornadoes for three "seasons" for the Mississippi, Louisiana, and Alabama portions of the Gulf Coast Type A distribution The period December through March shows a definite

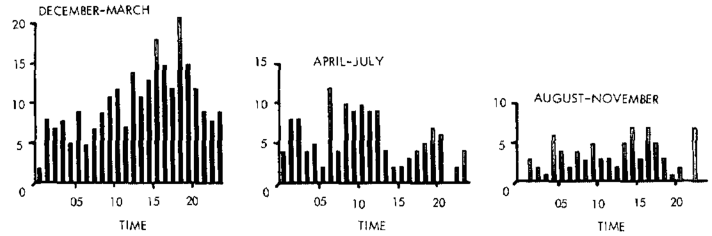

FIGURE 22.—Graphs of the "seasonal" diurnal distributions of tornadoes for the Gulf Coast areas of Alabama, Mississippi, and Louisiana. See text for discussion of "seasons."

bias toward a late afternoon or early evening maximum with the mean hour of occurrence 1800 LST. On the other hand, the graph for April through July shows a bias toward a morning or early afternoon maximum with the mean hour of occurrence being 1000 LST. A t-test on the difference between the two means indicates that two populations are being sampled. It is not difficult to appreciate how the complex graphs of the Gulf Coast Type can result *in this area.*

It is possible to build a hypothesis for why the morning bias in the Gulf Coast States exists. It is fairly well known that subtropical coastal areas tend to have a maximum of cloudiness in the morning. This has variously been ascribed to the semidiurnal pressure wave and differential cooling rates between land and sea. As House (1963) points out, the more rapid land nocturnal cooling can lead to an increase in the Laplacian of the thickness field, which in turn tends to create low-level cyclonic vorticity and convergence over the land. Additional evidence has recently been provided by Rasmusson (1967), who finds a tendency toward divergence aloft and convergence near the surface in the early morning. If this is combined with radiative cooling from the cloud tops, conditions for intense morning convection can be visualized.

These arguments represent hypotheses and speculations that seem to have some applicability for the large-scale pattern shown in figure 12. However, they are not well established and so do not account for much of the finer detail. Thus, they are tentative and incomplete at best.

SQUALL LINE MOVEMENT

Severe thunderstorms very often assume a line structure that propagates downstream over a significant length of time. These lines of severe thunderstorms maintain their potential for tornadic activity throughout the mature stage. It is apparent, then, that given preferential origin areas and a conservative movement rate, movement of tornado-bearing structures into an area can affect the diurnal-distribution curves.

The Plains Type B distribution in eastern Missouri and southern Illinois is an ideal area for examining the influence of squall line movement. This area is located some 8 to 12 hr from favored squall line origin areas in central and eastern Kansas.

To test the hypothesis of travelling structures the hourly radar maps of the Radar Analysis and Development Unit (1956–1964) were used to trace back the echoes with which early morning tornadoes in eastern Missouri and southern Illinois were associated. The period investigated is only 1956 to 1964 with some data gaps.

Of the 29 cases investigated, seven were classed as "local" occurrences because the echoes developed in the area. The remaining 22 cases are of the travelling squall line type. Many of the lines developed in central and eastern Kansas and moved eastward to cause tornadoes between 0000 and 0300 LST in the Plains Type B of southern Illinois. It appears then that the travelling tornado-bearing structure is important at least in one area. Other studies must be carried out, however, before any generality of this influence can be shown.

SUMMARY

The explanations suggested above are no more than speculations for particular areas. It seems likely that little more can be done before a general model for tornado formation is developed. Even then the diurnal variations of the pertinent processes are likely to be little investigated. It is hoped that the meteorologists interested in tornado-genetic processes will find food for thought in the spatial and temporal patterns that have been shown to exist in this paper, and that they will be able to provide a general explanation.

6. CONCLUSIONS

The major conclusions reached in this investigation may be listed as follows:

1) There is much greater variation in the diurnal distribution of tornadoes than has been previously recognized.

2) The three major diurnal distribution types are organized into spatial units that suggest spatial variations in tornado and tornado-related processes.

3) The traditional concept of the shape of the diurnal curve of tornado occurrence is valid for about two-thirds of the central and eastern United States.

4) Interhourly variation is considerable for the remaining one-third of the study area and multimaximal distributions are common.

5) Secondary maxima are common and distinctive even where a well-developed primary maximum exists.

6) No explanation of the spatial and temporal variations described can be provided on the basis of present knowledge; however, seasonal changes in thermodynamics and dynamics seem important in the broad-scale picture while squall line movement, origin areas, and topographic controls may be important locally.

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